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C.T. Liu (PRSM) and J.N. Yang (UCI), "Investigating the Strain Rate Effect on the Equivalent Initial Crack Size in a Particulate Composite Material"

4th Int. Conf. on Computational Stochastic Mechanics **(Statement A)**
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Investigating the Strain Rate Effect on the Equivalent Initial Crack Size in a Particulate Composite Material

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Abstract

In this study, the effect of strain rate on the equivalent initial crack size in a particulate composite material is investigated. The results of analyses indicate that the equivalent initial crack length is insensitive to the strain rate and it follows the second asymptotic distribution of maximum values.

Introduction

An important engineering problem in structural design is evaluating structural integrity and reliability. It is well known that there are two different structural design philosophies, safe-life and damage-tolerance. According to the safe-life design philosophy, no crack will initiate in the structure during its design life. In other word, the service life of a structure is terminated once a crack is predicted or detected. On the other hand, the damage-tolerance design philosophy presumes the existence of cracks and defects in the structures and guards against their unstable growth. In other words, the damage-tolerance design approach seeks to avoid the growth of the existing crack to a critical size. The accurate determination of the initial crack size governs the assessment of the integrity and reliability of the structure. Reliable performance of a structure in critical applications depends on assuring that the structure in service satisfies the conditions assumed in design and life prediction analyses. Reliability assurance requires the availability of nondestructive testing and evaluation (NDE) techniques to characterize discrete cracks according to their location, size, and orientation. This leads to an improved assessment of the potential criticality of individual cracks. To achieve this goal, an inspection criterion, regarding the size of the crack and the inspection interval, needs to be developed. The inspection criterion should not be driven by inspection capability of NDE methods, but rather, selection of NDE methods should be driven by real engineering requirements. Therefore, in order to develop the inspection criterion, the initial crack size in the material needs to be determined.

It is well known in the aerospace industry that the initial crack size in metals can be determined using experimental results, such as fractographic data or S-N data (1-2). From the experimental S-N data, one can determine the critical crack size at the time of failure.

Then, the initial crack size is computed from the critical crack size by conducting a crack growth analysis backward.

While the basic concept for determining the initial crack size in particulate composite materials is similar to that for metallic materials used in aircraft industry, there are significant differences in the technical approach as shown in Ref. 3. In Ref. 3, a technique was developed to predict the initial crack size in a particulate composite material, containing hard particle embedded in a rubbery matrix, under a constant strain rate condition. The fracture and the crack growth behavior of the particulate composite material investigated in the previous study are highly dependent on the strain rate. Therefore, in order to develop a reliable inspection criterion, it is indispensable to determine the effect of strain rate on the equivalent initial crack size.

In this study, the effect of strain rate on the equivalent initial crack size (EICS) in a particulate composite material, which is the same material used in the previous study as mentioned in Ref. 3, was determined. Two different strain rates, 0.727 min^{-1}, and 18.182 min^{-1}, were considered. The statistical distribution functions of the equivalent initial crack size and the critical crack size were determined. The results of the equivalent initial crack size and statistical analyses are discussed.

Analytical Analysis

To determine the equivalent initial crack size, the following information is needed: (1) crack growth rate parameters, (2) critical stress intensity K_{IC} and threshold stress intensity factor K_{th} under which crack will not grow, and (3) time to failure data under constant strain rate. Crack growth rate parameters as well as K_{IC} and K_{th} are determined experimentally using pre-cracked specimens. Time-to-failure data are also obtained experimentally using specimens without a pre-crack.

For pre-cracked specimens, the stress intensity factor K_I is given by

$$K_I = \sigma (\pi a)^{1/2} f (a/w) \qquad (1)$$

in which σ is the applied stress, f (a/w) is the geometric correction factor, a is the crack length, and w is the width of the specimen. The functional relationship between f (a/w) and a/w is shown below.

$$f (a/w) = 0.7722(a/w)^3 + 0.9253(a/w)^2 + 1.095(a/w) +1.005 \qquad (2)$$

For a specimen subject to a constant strain rate, the stress intensity factor K_I reaches the critical stress intensity factor K_{IC} at the instant of fracture, and the corresponding crack size is denoted by a_c, referred to as the critical crack size or the terminal crack size. It follows from Eq. (1) that

$$K_{IC} = \sigma_c (\pi a_c)^{1/2} f (a_c/w) \qquad (3)$$

where σ_c is the critical stress at fracture.

The crack growth rate da/dt has been shown to be a power function of the stress intensity factor K_I, i.e.,

$$da/dt = Q\, K_I^m \tag{4}$$

in which m and Q are crack growth rate parameters.

When a specimen without pre-crack is subjected to a constant rate, the entire loading history and hence the stress history $\sigma = \sigma(t)$ can be measured, including the critical stress σ_c at the time of fracture, t_c. For a given critical stress intensity factor K_{IC} (material constant), the critical crack size a_c can be computed from Eq. (3). Consequently, the initial crack size a_o at $t = 0$ can be obtained by integrating Eq. (4), based on the terminal condition (a_c, t_c) and the stress history $\sigma(t)$.

Experimental Analysis

In this study, two set of constant strain rate test were conducted. In the first set of tests, uniaxial specimens without pre-crack were conducted at two different strain rates of 0.727 min^{-1} and 18.18 min^{-1}. The specimen's dimensions are 0.375 in. wide, 2.75 in. height, and 0.5 in. thick. The results of this set of tests together with the crack growth parameters, which were determined from crack propagation tests under a different research project and are shown in Tables1 and 2, were used to estimate the EICS. The second set of constant strain rate tests were conducted on specimens with and without pre-crack at four different strain rates, 0.067 min^{-1}, 0.67 min^{-1}, 6.7 min^{-1}, and 66.7 min^{-1}. The specimen's dimensions are 1.0 in. wide, 3.0 in. height, and 0.2 in. thick. For the pre-cracked specimen, a single edge-crack was cut at the edge of the specimen using a razor blade. Three different crack sizes, 0.1 in., 0.2 in., and 0.3 in., were considered. The results of the second set of tests were used to verify the estimated EICS.

Statistical Distribution of Equivalent Initial Crack Size and Critical Crack Size

The results of the analysis show that the EICS, a_o, as well as the critical crack size a_c vary from specimen to specimen. Hence, the statistical distribution of these quantities should be determined. In this study, four statistical distribution functions, (1) normal distribution, (2) two-parameter Lognormal distribution, (3) two-parameter Weibull distribution and (4) second asymptotic distribution of maximum values, were considered. The goodness of fit for different distributions has been conducted using the Kolomogorov-Smirov test.

Results and Discussion

In the crack growth analysis, the effect of the threshold stress intensity factor for the onset of crack growth, K_{th}, was not considered. Hence, the flaw size, a_o, at time, t, equal to zero represents the EICS with $K_{th} = 0$. By knowing K_{th}, the time t* corresponding to K_{th} can be obtained from the K_I versus t plot, and, similarly, the crack size at t*, denoted by a*, can be obtained from the a versus t plot. The results of the analysis are shown in Tables 1 and 2. According to Tables 1and 2, it is seen that a_o and a* are very close to each other. This indicates that the accuracy of the crack growth model and the developed EICS predictive model is excellent.

Based on the analysis, the estimated EICS for strain rates equal to 0.727 min^{-1} and 18.182 min^{-1} are 0.119 in. and 0.146 in., respectively. From Ref. 3, the EICS for strain rate equal to 0.067 min^{-1} is 0.13 in. The variation of EICS among the three different strain rates is within the scatter of experimental data. Therefore, on the first approximation, it can be assumed that the EICS is independent of strain rate, and the averaged EICS is equal to 0.132 in. The independence of the EICS on the strain rate suggests that the EICS is a material property, which depends on the microstructure of the material.

Just FYI

Typical plots of statistical distributions of a_o are shown in Figs.1-4. For a comparison purpose, experimental data, shown as circles, are also included in these figures. It is seen that the Weibull distribution fits the experimental data the best, which is consistent with the results of the goodness of fit analyses. However, the differences among the four statistical distributions are very small. Under this condition and based on a physical reasoning, the second asymptotic distribution of maximum values is selected for the statistical distribution function of a_o. The results of statistical analyses of a_c are similar to that of a_o.

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In this study, the equivalent initial crack is a hypothetical crack assumed to exist in the material. It characterizes the equivalent effect of an actual initial crack in the material. The equivalent initial crack is not a physically observable initial crack. Therefore, the predicted equivalent initial crack must be justified using applicable test data. In other words, the predicted EICS needs to be verified experimentally. To achieve this goal, uniaxial edge-cracked tensile specimens with different initial crack lengths were tested at four different strain rates as indicated in the Experiments Analysis section of this paper. The tests results, plotting the maximum stress, σ_{max}, versus the corresponding time, t_{max}, are shown in Fig. 5. By shifting the un-precracked specimen data vertically downward until they superpose upon those of the pre-cracked specimen, we can obtain an estimate for the initial flaw size in the un-precracked specimen. The dashed lines in Fig. 5 represent the vertically shifted curves. According to Fig. 5, the initial crack size in the un-precracked specimen is approximately equal to 0.1 in., which compares well with the predicted value of 0.132 in.

Conclusion

In this study, the effect of strain rate on the equivalent initial crack size is investigated. The results of analyses indicate that, on the first approximation and for the engineering application purpose, it can be assumed that the equivalent initial crack size is independent of strain rate. It also indicates that the equivalent initial crack size and the critical crack size follow the second asymptotic distribution of maximum values.

References

(1) Yang, J.N., Manning, S.D., Rudd, J.L., and Bader, R.M. (1995), "Investigation of Mechanistic-Based Equivalent Initial Flaw Size Distribution," Proceeding of the 18th Symposium of ICAF, Melbourne, Australia, 385-403.

(2) Yang, J.N., Manning, S.D., and Newman, J.C., Jr., (1997), "Equivalent Initial Flaw Size Distribution for Notches in 2024-T3 Aluminum, Accounting for Short Crack Effect," Proceeding of 1997 International Conference on Structural Safety and Reliability, Kyoto, Japan.

(3) Liu, C. T. and Yang, J. N. (2000), "Determination of Equivalent Initial Flaw Size in a Particulate Composite Material," Proceeding of the 8th ASCE Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability, Notre Dame, IN.

Table 1. Crack Growth Data (Strain Rate = 0.727 min.$^{-1}$)

Specimen	a_c	t_c(sec)	a^*	t^* (sec)	a_0	σ_{max}
Specimen 1	0.12965	23.25800	0.12068	13.48200	0.11793	144.67904
Specimen 2	0.12964	24.61500	0.12030	14.44200	0.11753	144.68937
Specimen 3	0.12918	24.89800	0.12052	15.39600	0.11790	145.11513
Specimen 4	0.12966	24.86500	0.12046	14.83700	0.11778	144.66927
Specimen 5	0.12608	23.59600	0.11785	14.67700	0.11545	148.04800
Specimen 6	0.13168	23.82600	0.12287	14.17000	0.12012	142.81772
Specimen 7	0.13145	23.89300	0.12338	15.04000	0.12084	143.03157
Specimen 8	0.13069	23.96000	0.12171	14.21300	0.11902	143.71641
Specimen 9	0.13057	23.24400	0.12281	14.68500	0.12029	143.83377
Specimen 10	0.13100	22.77200	0.12256	13.56700	0.11988	143.43883
Specimen 11	0.13029	22.62700	0.12124	12.83800	0.11846	144.08449

K_{IC} = 126 psi. sqrt(in); K_{th} = 89 psi. sqrt(in)
m = 2.066; $Q = 3.4127 \times 10^{-6}$

Table 2. Crack Growth Data (Strain Rate = 18.182 min.$^{-1}$)

Specimen	a_c	t_c(sec)	a^*	t^* (sec)	a_0	σ_{max}
Specimen 2	0.15425	1.52410	0.14396	0.92817	0.14258	197.65681
Specimen 3	0.15543	1.56840	0.14530	0.97216	0.14386	196.30417
Specimen 4	0.15993	1.62110	0.15018	1.04930	0.14888	191.26692
Specimen 5	0.15268	1.47570	0.14237	0.88766	0.14114	199.48143
Specimen 6	0.15476	1.45990	0.14506	0.89909	0.14379	197.07326
Specimen 7	0.15505	1.46360	0.14471	0.87206	0.14348	196.73795
Specimen 8	0.16073	1.50860	0.15029	0.89749	0.14883	190.39449
Specimen 9	0.16006	1.49300	0.14973	0.88745	0.14826	191.12525
Specimen 10	0.15765	1.50720	0.14717	0.89387	0.14575	193.79063
Specimen 11	0.15902	1.52830	0.14858	0.91423	0.14711	192.26973
Specimen 12	0.16086	1.49390	0.15115	0.92008	0.14976	190.25419
Specimen 13	0.15963	1.47920	0.14965	0.89482	0.14819	191.60053

K_{IC} = 200 psi. sqrt(in); K_{th} = 125 psi. sqrt(in)
m = 2.066 ; $Q = 2.7612 \times 10^{-5}$

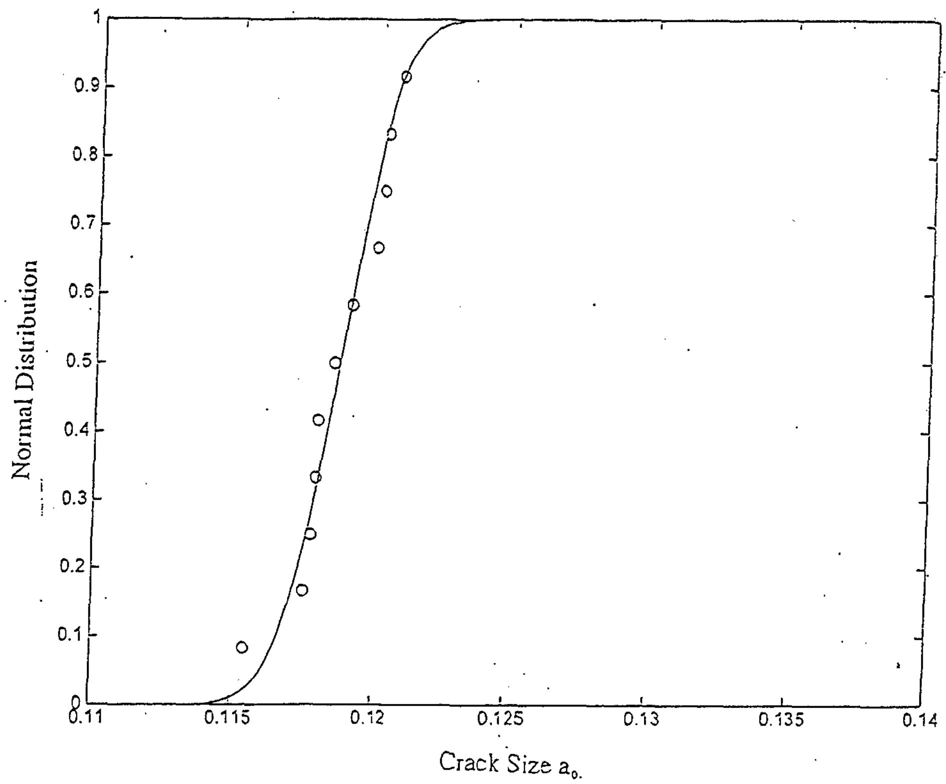

Fig. 1. Normal Distribution Plot for a_o.

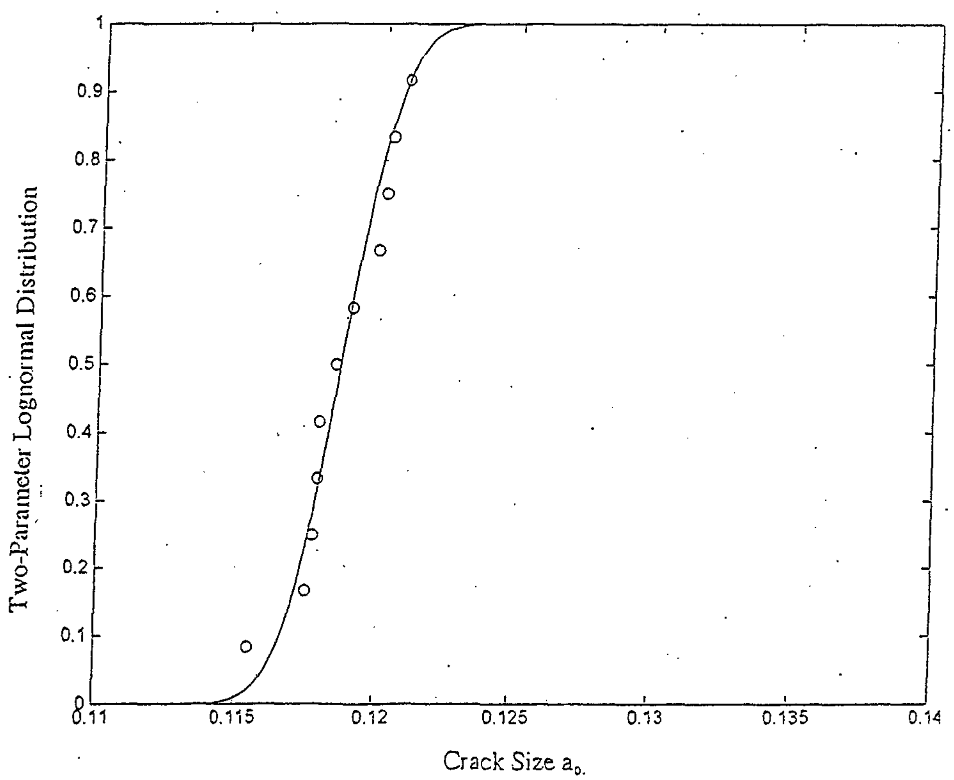

Fig. 2. Two-Parameter Lognormal Distribution Plot for a_o.

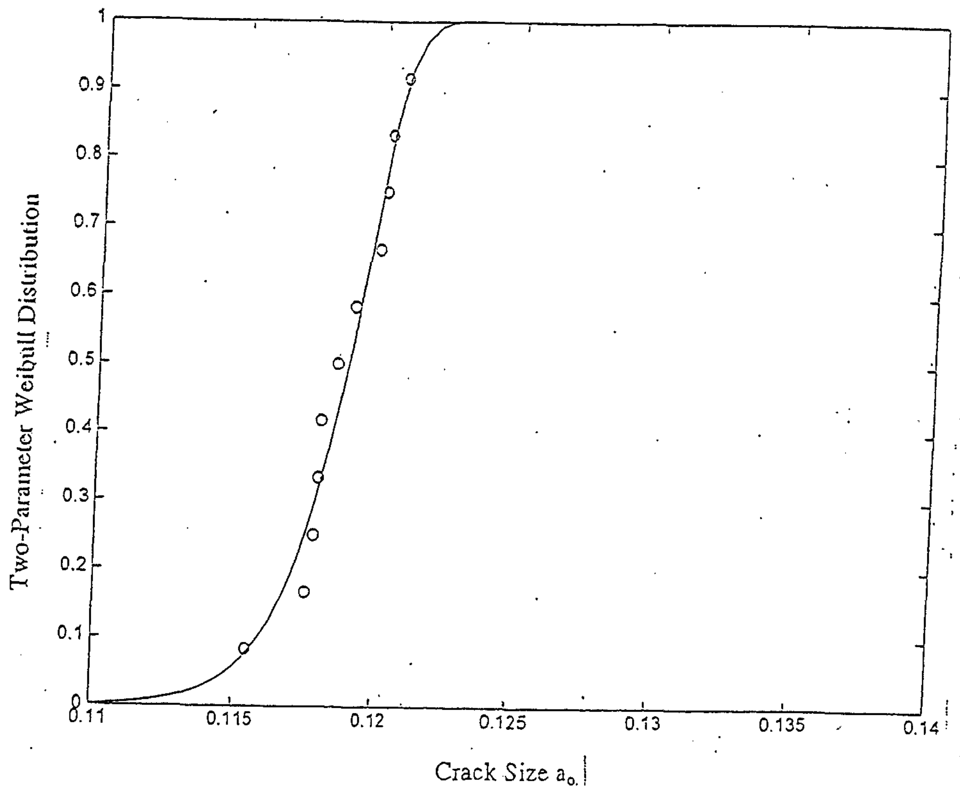

Fig. 3. Two-Parameter Weibull Distribution Plot for a_o.

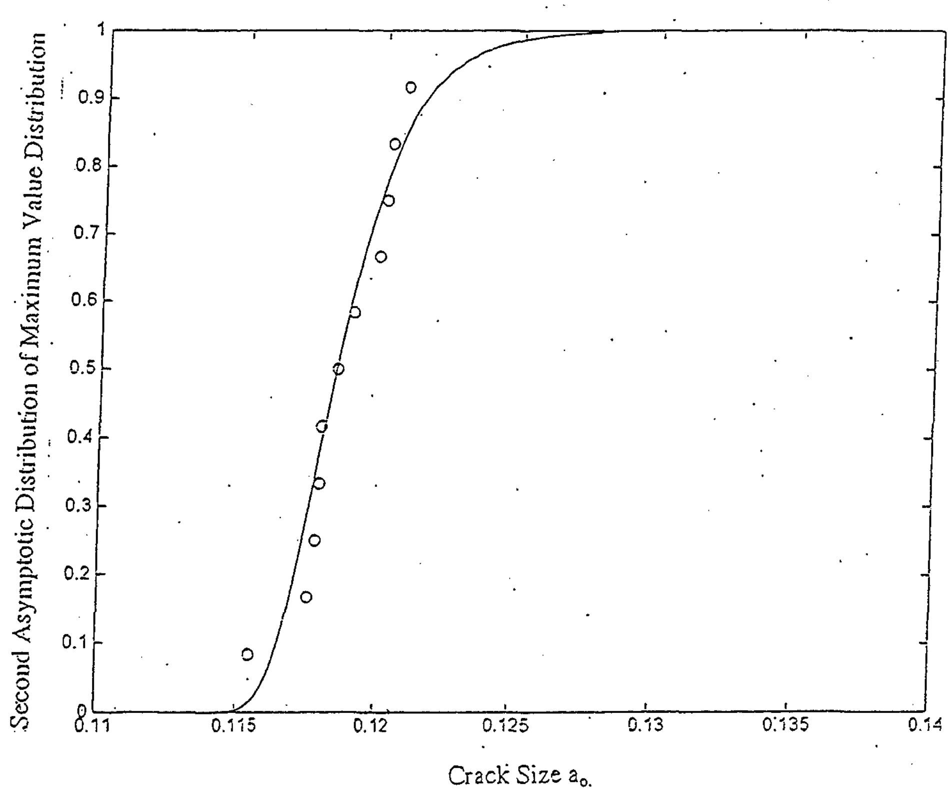

Fig. 4. Second Asymptotic Distribution of Maximum Value Plot for a_o.

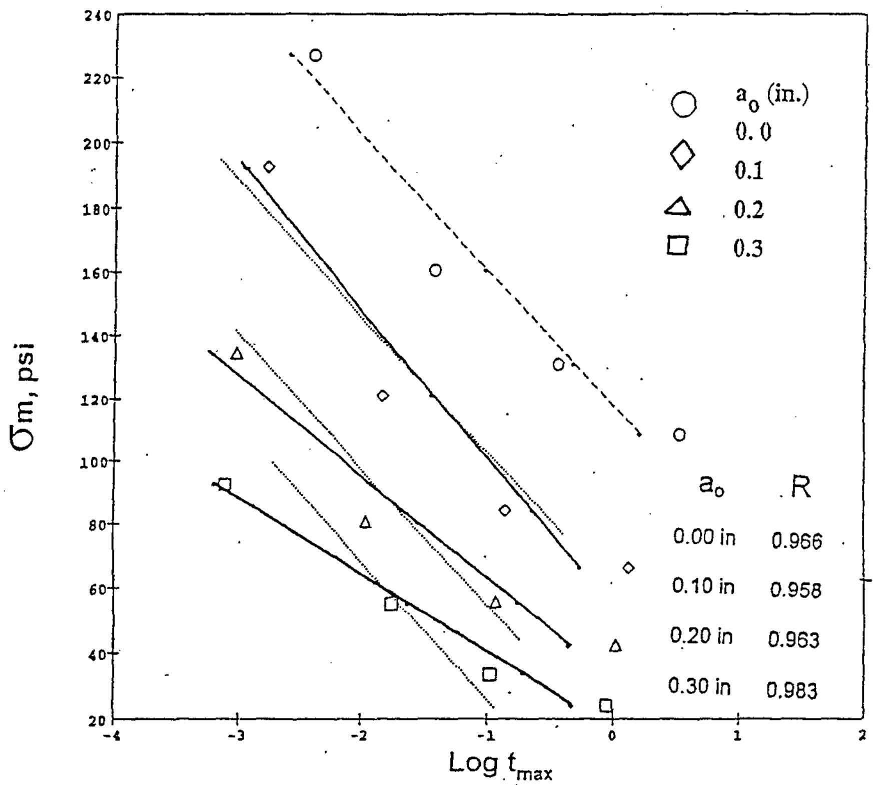

Fig. 5. Maximum Stress Versus Maximum Time.